Final Report

LASER DOPPLER VELOCIMETER AND HIGH SPEED IMAGING SYSTEM FOR FLUID DYNAMICS, COMBUSTION AND CHEMICAL KINETICS RESEARCH

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ABSTRACT

A Laser Doppler Velocimetry (LDV) system and a high speed imaging system were acquired for the Department of Defense (DoD) Grant N00014-97-1-0511 and setup in the Combustion and Emission Control Laboratory at Clark Atlanta University. These instruments have provided an integrated diagnostic system in the areas of combustion, propulsion, emission control, chemical kinetics and fluid dynamics for time resolved flow visualization and detailed quantitative measurements of flow velocities in complex reacting and non-reacting flows.

Research projects supported with the acquired instruments included: turbulent premixed combustion, optimization of non-thermal plasma discharge for pollution control, droplet behavior under supercritical conditions, interaction between acoustic waves and fuel droplets and sprays, and combustion instabilities in ramjet combustors. The instruments will also be used on the precombustion pyrolytic degradation of hydrocarbon fuels under normal and microgravity conditions. Seven (7) undergraduate and graduate students from the Department of Engineering and Department of Chemistry at Clark Atlanta University have, so far, been trained and educated on the instruments.

The acquired instrumentation has significantly strengthened the University's research infrastructure, and enhanced CAU's capabilities to undertake research that is relevant to the critical technology areas of DoD. These include the chemical kinetics, combustion and propulsion, and fluid dynamics programs of the Army Research Lab (ARL); the aerodynamics, turbulence and internal flows, air-breathing combustion, space power and propulsion, and physical mathematics and applied analysis programs of the Air Force Office of Scientific Research (AFOSR); and the turbulence, propulsion and flow structure interactions, and propulsion programs of the Office of Naval Research (ONR).

Two DoD funded projects, the nonthermal plasma discharge (NTPD) study and the sub- and supercritical behavior of fuel droplets and jets, and three NASA funded projects, turbulent premixed combustion, droplet behavior under supercritical conditions and combustion instabilities in ramjet combustors, have greatly benefited from the acquired instruments. In less than two years since the instruments have been purchased and installed, seven (7) technical papers and one (1) Ph.D. thesis on their applications have been produced.

1. INTRODUCTION

The need and ability to make accurate and detailed experimental measurements in practical combustion systems involving high-temperature, multi-species, multi-phase turbulent flows with chemical reactions present the combustion scientist with formidable challenges. In the past, probes of hostile environment, as well as the tendency of probes to modify the flows they are intended to measure, have limited their accuracy and complicated the interpretation of results. Laser diagnostics have opened new horizons for the combustion and fluid flow scientist. Through the use of lasers, it has become practical to make accurate measurements of temperatures, concentrations, densities, and velocities with high spatial and time resolutions in

practical combustion and fluid flow situations, without disturbing the flow field under study. These innovative measurement technologies and instruments have undoubtedly improved the understanding of combustion processes, which will eventually lead to the development of more efficient and environmentally acceptable combustors.

Fluid flow research calls for the development of theoretical models that are capable of describing the complex flow phenomena such as those in the compressor, around an aircraft body, and reacting flows in the combustion chamber. On the other hand, the theoretical or numerical results generated by computational fluid dynamic (CFD) research need to be verified and the computer codes validated by experimental data. The development of appropriate measurement techniques that can provide the experimental data needed to guide the theoretical efforts becomes, again, critical for the success of research.

Clark Atlanta University has been developing a Combustion and Emission Control Laboratory during the past three years. Current research projects include studies on turbulent reacting flows, pulsed combustors, non-thermal plasma discharge, droplet combustion, and low-NOx combustor development. The two instruments acquired from this grant, a three-dimensional Laser Doppler Velocimetry (LDV) and a high speed imaging system have been used for most of these projects. The facilities have enhanced and expanded the scope of the projects CAU can undertake and empowered CAU to successfully undertake research projects in areas critical to the national security functions of DoD such as fluid dynamics, combustion and propulsion, and chemical kinetics. They have also greatly strengthened the capabilities of the CAU Departments of Engineering, Chemistry, and Mathematics to attract, educate, and graduate more underrepresented minority students in science and engineering.

2. DESCRIPTION OF INSTRUMENTATION

2.1 Three Dimensional Laser Doppler Velocimeter

Laser Doppler Velocimetry (LDV) is a powerful technique used for highly accurate measurements of fluid velocity in liquid or gaseous flows. Scattered light from particles passing through the probe volume contains a Doppler frequency proportional to the particle velocity. Very small probe volumes can provide highly resolved velocity profiles and allow measurements close to a wall or object in the flow. Measurements can also be conducted in extremely harsh environments such as in combustion processes and in explosions.

The three-dimensional LDV system is a state-of-the-art fiber optic system designed and manufactured by TSI incorporation, St. Paul, MN. TSI is an industry leader in laser Doppler flow characterization and particle size diagnostics. The system provides superior alignment stability and is designed to virtually eliminate the need for internal adjustments. The optical transmitter is rugged and easy to set up. Frequency shifting applied to the input beams acts to offset the Doppler frequency, providing improved dynamic range and allowing distinction between froward and reverse flow directions. The 3-D system uses different wavelengths to form independent overlapping probes for orthogonal flow directions. This greatly reduces the time required for mapping multi-dimensional flows. In addition, fiber optic probes are used to

isolate the transmitter and receiver optics from their electronics. This enables application in harsh environments, which protect the more sensitive electronic and electro-optical system components.

The LDV signal processor, Doppler Signal Analyzer (DSA), provided by TSI employs the latest innovation in analog and digital electronics for maximum processing efficiency and reliability. Trans-impedance pre-amplifier, high speed Analog-to-Digital Converters (ADC), advanced array processors, and the Fourier Transform Burst Detector technology used in the design have contributed to the outstanding performance. The DSA is capable of processing Doppler frequencies as high as 150 MHz. Two 160 MHz ADC's perform simultaneous sampling of the quadrature mixed signals, resulting in an equivalent sampling frequency of 320 MHz. The DSA has an operating bandwidth of up to 145 MHz. This is superior to processors, which have operating bandwidth much smaller than their frequency range. The DSA implements the optimal method of frequency estimation, the Discrete Fourier Transformation, to determine the Doppler frequency, and then the velocity. The Fourier transform involves the matching of noisy Doppler signal with sine waves of discrete frequencies.

This is a distinct advantage over other signal processing methods because correlating the signals with pure signals instead of noisy signals can downplay the effect of the noise. Consequently, accuracy is maintained, even in difficult environments where the signal to noise ratio (SNR) may deteriorate to below –6 dB. In addition, reliable measurements can be obtained independent of the number of signal cycles recorded, and the DSA does not produce a frequency bias when the SNR deteriorates. The DSA incorporates an innovative signal burst detection system that uses both the Fourier transform and signal power in the time domain. The Fourier Transform Burst Detector performs up to 20 million Fourier transforms per second. It eliminates the dependence of the signal detection on the signal and noise amplitude, favoring the SNR. A detailed listing of the order for the LDV is given in Appendix A.

2.2 High Speed Imaging System

The high speed imaging system acquired is a Kodak EktaPro Motion Analyzer, which consists of three primary components: an imager, a processor, and a monitor (Eastman Kodak Company, NY). The system is a powerful imaging tool designed to capture events at 1,000 to 12,000 pictures per second with resolution of 192 x 239 pixels, in bright sunlight to near darkness (1.5 lux). The analyzer allows simultaneous recording of two views of the same subject, or two separate but related subjects, by simply adding another imager. It has a multi-channel data link port, allowing the measurement of voltage levels of actuators, sensors and other electrical/electronic devices with dynamic characteristics, and recording of data along with the video images.

The high speed imager features extremely fast electronic shutter speeds, with exposures as short as 10 microseconds to "freeze" an object in motion. The motion analysis processor EktaPro EM can capture and store 1,000 full-frame or 12,000 split-frames per second. The stored images can be played back at a rate ranging from single step up to full speed in both forward and reverse mode, be displayed on a standard video monitor, copied to a VCR for archiving, outputted to video printer or downloaded to a computer workstation for display and

digital image analysis. The Kodak EktaPro motion analysis workstation provides powerful software for digital image enhancement and quantitative motion analysis. A detailed listing of the order for the high speed imaging system is given in Appendix B.

3. RESEARCH SUPPORTED BY THE ACQUIRED INSTRUMENTATION

Several research projects funded by DoD and NASA have been supported with the acquired laser Doppler velocimetry and high speed imaging system. These cover such topics as turbulent premixed combustion, non-thermal plasma discharge, droplet behavior under supercritical conditions, and combustion instabilities in ramjet combustors. Some of the research results from these projects are discussed below.

3.1 Turbulent Premixed Methane-Air Combustion

An understanding of the premixed turbulent combustion of natural gas or methane is essential since: (1) the characteristic dimensions and flow rates of most industrial equipment are often large enough for flows to be turbulent, and (2) many industries are now pursuing lighter hydrocarbon alternative fuels and the use of premixed combustion processes to reduce pollutant emissions [1]. In spite of the many prior studies on methane-air combustion [2-8], the fundamental mechanisms and kinetics involved in the premixed combustion process are not well understood. Despite extensive research work on turbulent flow structures, the interactions between the chemical reactions and the turbulent flow are not clearly understood. The current prediction models are not reliable, and much of the analytical work fails to properly handle the coupled non-linear fluid dynamic and chemical complexities. There is clearly a need for better understanding and more accurate and powerful approaches for addressing this very basic combustion problem. The ability to measure and predict the coupled effects of complex transport phenomena through detailed experiments and modeling is critical and needed.

Particle image velocimetry (PIV) and Laser Doppler velocimetry (LDV) are two of most advanced techniques of unveiling flow and associated structures. PIV measures velocity over many points – a cross section – at one instant in time and offers a global image, while LDV provides the detailed time history at a point and gives a point information at each time. Although PIV and LDV work by different principles, they compliment each other well in many application areas. With the PIV measuring technique, the velocity of a flowing medium is measured by recording the displacement of small particles carried with the flow and subsequently analyzing the particle displacements recorded. Two or more short laser pulses fired with a known time separation illuminate particles embedded in a region of the flow. The particle positions are recorded by means of a CCD camera. The particle displacements in the flow field are found from the displacements in the image plan. Knowing the magnification of the imaging and the time separation between the laser pulses, the velocity projections on the measuring plane are found.

The schematic diagram of the experimental set-up for the turbulent premixed methane-air combustion using the LDV measurement systems is shown in Fig. 1 [9]. The LDV system used in this study was a TSI three-component (3-dimension) Laser Doppler velocimeter (Thermal Systems Inc., St. Paul, MN), consisting of the compact TRCF-3 ColorBurst multicolor beam separator, the ColorLink multicolor receiver, the S75-3 IFA 750 processor, the PermaFiber fiberoptic probes, and the FIND and PHASE data analyzer. The system measured the three components (dimensions) of the instantaneous velocity. The strong beams of a multicolor argon-ion laser (green/514.5 nm, blue/488 nm and violet/476.6 nm) were used to measure the velocity components. The laser beams were provided by a 5 W Coherent Innova-90 argon-ion laser (Coherent Inc., Santa Clara, CA), and split by a TSI TRCF-3 ColorBurst. The three-component velocities were measured by a dual-axis fiberoptic system, consisting of a 83-mm diameter two-component fiberoptic probe for 514.5 nm (green) and 488 nm (blue), and a 83-mm diameter single-component fiberoptic probe for 476.5 nm (violet). Both probes had the following parameter values: beam spacing - 5 mm; focal length - 350.0 mm; half angle - 4.096 degree; receiver focal length - 310.0 mm; and receiver optic axis elevation - 1.0 mm. The laser beam diameter at the front of the probe optics was 2.2 mm. The fringe spacing for channels 1, 2, and 3 (green, blue and violet) were 3.062, 3.416 and 3.332 μm, respectively. The two probes were mounted on a three-axis traverse at a certain angle. For each dimension measurement, two same-wavelength laser beams at a certain angle were shot simultaneously. When the two laser beams hit a moving particle, it produced a Doppler shift, which was reflected back to the optic probe for

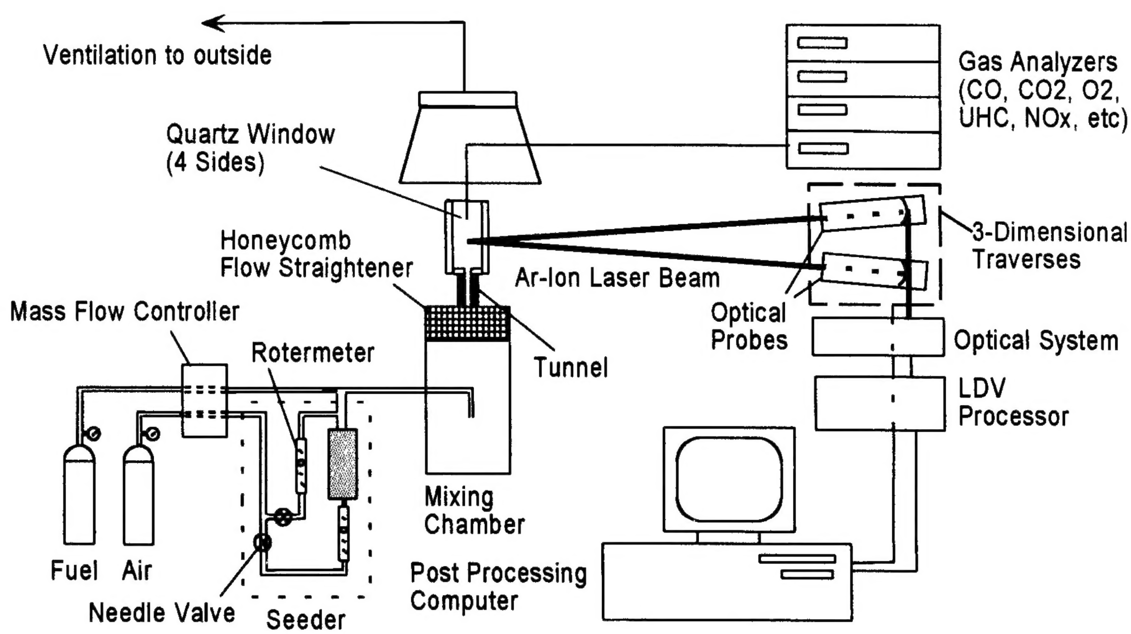

Fig. 1 Schematic of the experimental setup for turbulent premixed methane-air combustion.

velocity calculation.

As background lights do not affect the LDV measurement, there was no need for a light filter as was required for the PIV. Because the LDV is a point measuring technique, the traverse was provided to move one or two fiberoptic probes in three orthogonal directions. The traverse provided maximum 600-mm travel distance with 0.01-mm resolution on each direction. The two probes could be adjusted for a wider range of focal distances. Because of the symmetry in the X direction, only two dimension measurements (Y and Z directions) were needed in this study. One probe with the 514.5 nm (green) and 488 nm (blue) lasers was used for the Z and Y directions, respectively. The probe used for the Y and Z measurements was oriented in the X direction.

Since LDV is a point measuring method, several hundreds of measurements were taken and used to make a flow structure plot by means of the computer software "TecPlot 7.5" (Amtec Engineering Inc, Bellevue, WA), as shown in Fig. 2. Figure 2 indicates that the main stream of the cold flow from the LDV measurements was about 4 mm wide, close to the nozzle width, and moved up to about 65 mm (16 D) above the nozzle without much disturbance. Beyond the 65

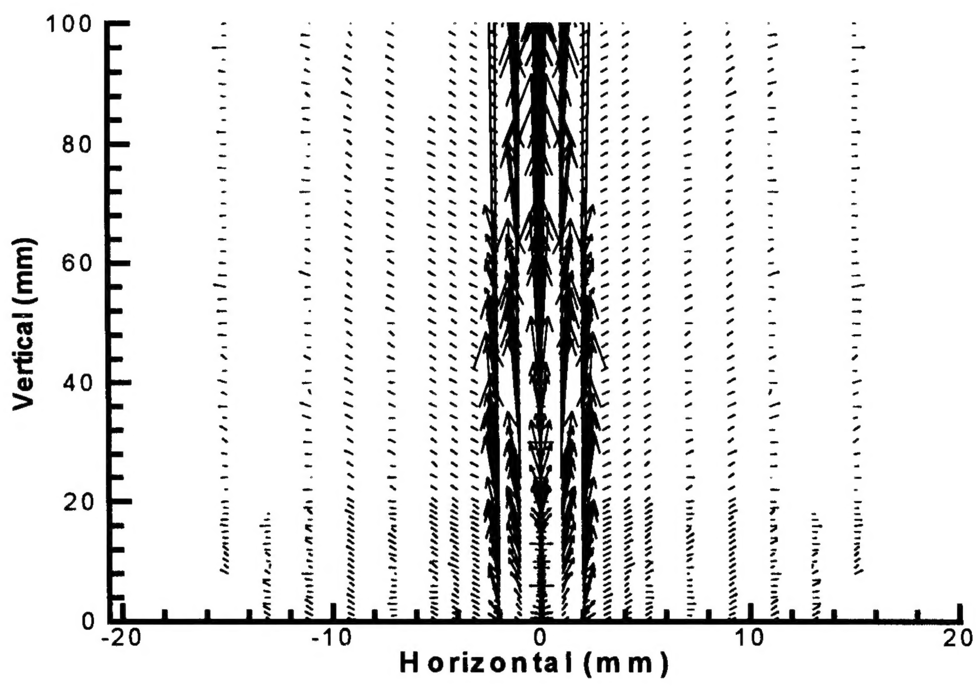

Fig. 2 The LDV velocity vector map of the cold flow (without flame)(linear airflow = 1.4 m/s, 122 × 4 mm marble nozzle.).

mm, the main stream became narrower and no large flow vortices were recorded. It is believed this may be due to the low LDV sensitivity to slow flows. According to DeCroix and Gould [10], <0.5 m/s flow velocities are problematic for LDV measurements.

The contour map of the cold flow for the LDV measurements is plotted in Fig. 3, and shows similar results to the vector map described above.

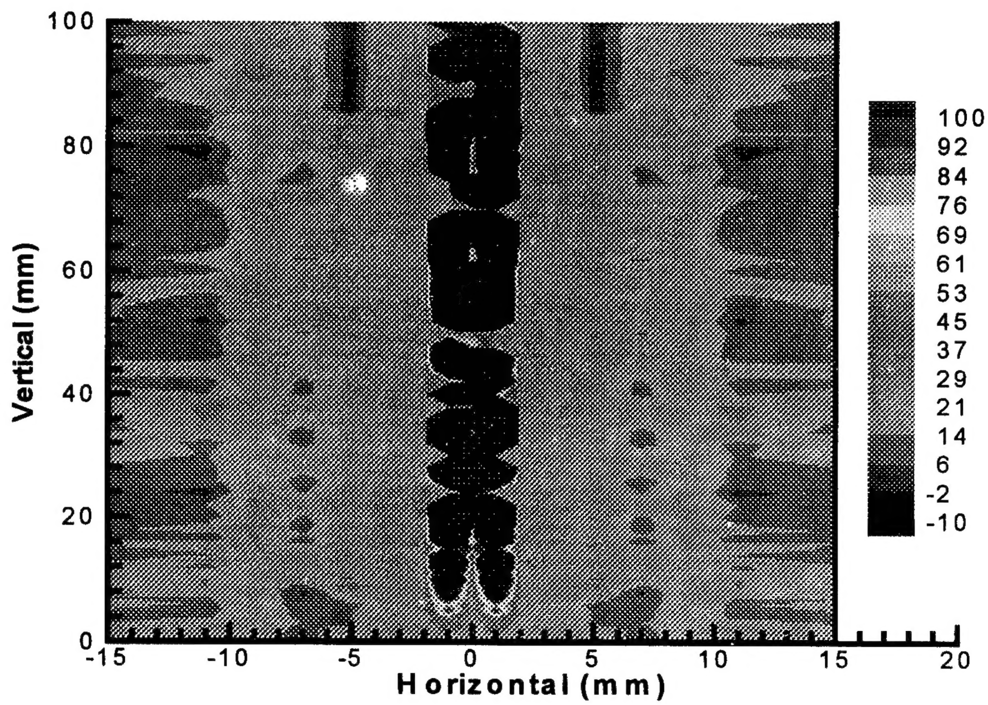

Fig. 3 The LDV velocity contour map of the cold flow (without flame) (linear airflow = 1.4 m/s, 122 x 4 mm marble nozzle).

3.2 Optimization of Nonthermal Plasma Discharge Electrochemical System

Nonthermal plasma discharge (NTPD) is one of the promising innovative technologies to destroy hazardous air pollutants and criteria pollutants contained in gas streams prior to atmospheric dispersion. When released into the atmosphere, the group of compounds collectively known as nitrogen oxides or NO_x contributes to photochemical smog, acid rain and ground-level ozone. Combustion processes are a primary source of NO_x emissions and finding a cost-effective technology to remove NO_x from combustion exhaust streams is essential. Within the Air Force infrastructure, diesel-powered aerospace ground equipment (AGE) have been identified as significant sources of NO_x. Given the operational constraints of AGE, an Air Force

study identified the Non-Thermal Plasma Discharge or NTPD as a promising technology for NO_x removal. As part of a program to optimize an NTPD system for this particular application, an investigation of the affect of discharge gap spacing on the electrical and chemical processes that occur in NTPDs was initiated. A number of experiments were performed to examine how the gap spacing affects the NO_x removal efficiency, discharge characteristics, and chemical reactions in a NTPD device. Gap spacings ranging from 0.8 to 4.0 mm were considered in this study. An optimum gap spacing for NO_x removal was observed at approximately 2 mm and based on the experimental data a physical explanation for the optimum was developed.

A schematic of the overall experimental setup is given in Figure 4 [11, 12]. A KODAK EKTAPRO High Speed Intensified Imager System and Nikon Micro lens were used to study the microdischarges. Specifications for the camera system include a frame rate of 30-6000 fps, a spectral sensitivity of at least 50% peak from 440 nm to 700 nm, and a variable gate time from 10-5000 μsec. Output from the imaging system was recorded on videotape via a 1/2" VHS VCR. The system was used to view the microdischarges from points both perpendicular and parallel to the breakdown channel.

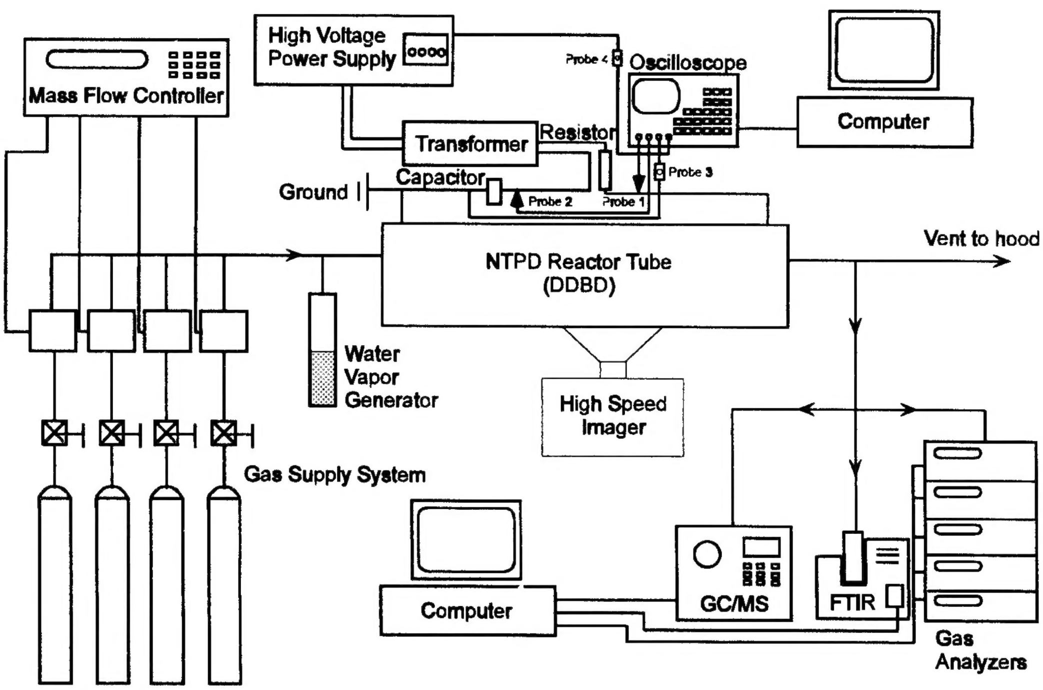

Fig. 4 Schematic of NTPD experimental setup.

Photographs, which were taken with the intensified high-speed imager in framing mode, revealed details of the microdischarge behavior [13]. The spectral range of the imager was from 400 to 800 nm and we assumed that the microdischarge images in this range represent the primary electron stream forming the discharge channel. It is important to note that the duration of the discharge image reflects only the integration of the excimers life within the channel and not the duration of actual charge transfer through the channel. During a single half power cycle

both the number and the physical dimensions of the microdischarges could be obtained directly by the imager. In order to extract further information from the optical observations the characteristics of the microdischarges were related to the transferred charge. For this analysis the double dielectric barrier discharge (DDBD) electrode configuration was presumed to be symmetric and we further assumed that all of the available surface charge was transferred through microdischarges in which chemical reactions were initialized. The specific reactions taking place within the microdischarges are determined by electron-molecular/atom collisions.

Fig. 5 High-Speed Images of Microdischarges at Different Gap Widths Gas composition: 1000 ppm NO, 2000 ppm H_2O, 10% O_2, N_2 balance, Room Temp, 1atm, Power =5 Watts, Frequency=400Hz, Residence time=0.46 s

A series of microdischarge images at different gap widths are presented in Fig. 5 [13, 14]. When obtaining these images, the residence time of the gas in the DDBD device was fixed. The fixed residence time was accomplished by changing the inlet flow rate when changing the gap spacing. The input power, driving frequency, and flow temperature were also fixed in each case, as was the gas mixture. The specific conditions under which the images in Figure 8 were obtained are given in the figure caption. Notice that with increasing gap spacing the radius, r, of the discharge increased significantly, while the number of discharges per half cycle dramatically decreased. The radius was found to vary from approximately 90 μm at the 1 mm gap width to 340 μm at the 4 mm gap width. The frame rate for these images was 1000 fps and the gate time was varied from 20 to 200 μs to obtain the clearest image.

3.3 Study of Droplet Behavior under Supercritical Conditions

Droplet and spray combustion dynamics play critical roles in the operation of liquid rockets, advanced gas turbines, and diesel engines. Because of their direct relation to practical spray combustion devices, the behaviors of liquid droplets in environments at supercritical pressure and temperatures under normal and microgravity conditions have long been of important research interest. About three decades have passed since the first experimental investigation of free droplet combustion under microgravity was presented by Kumagai and his co-workers [15]. Since then, extensive research has been conducted [16-23]. However, since there are still many difficulties involved in conducting droplet combustion experiments, many

questions still remain unanswered. One of the experimental difficulties is the ignition of a free droplet without disturbing its shape and movement. Kumagai et al [24] used an electrical spark to ignite a suspended droplet at ambient pressure; even so the electric spark still had some effect on the droplet's shape. Litchford and his co-workers [25] conducted the most recent and detailed work. Litchford *et al* used a pre-heated gas jet, which came from the bottom of the combustor to ignite the suspended droplet through convective heating. During the ignition process, the aerodynamic force of the hot flow deformed the droplet.

The droplet formation and release under high pressure and/or high temperature are also a difficult problem for droplet study. Litchford *et al* [25] and Kumagai *et al* [26] used a tiny tube to transfer the liquid fuel to a metal/quartz wire frame which was used for the droplet suspension. Because of the surface tension between the tube and the liquid, the droplet was difficult to transfer to the suspension wire, and the transferred droplet size was difficult to control. Further, after the droplet was transferred to the suspension wire, it was more difficult to release to a free droplet [24].

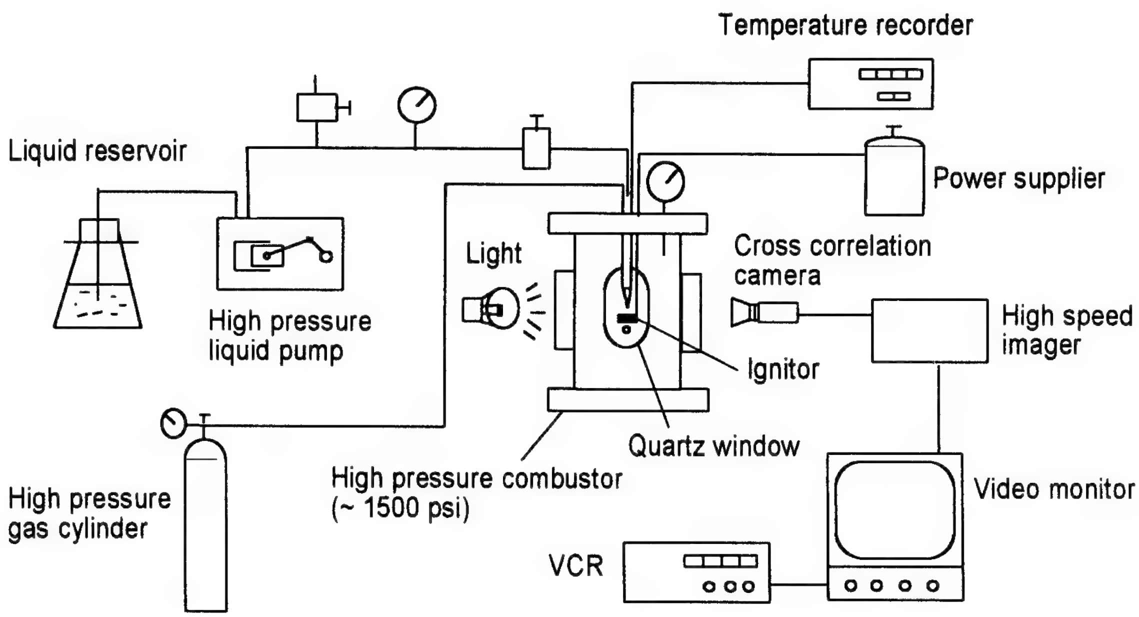

Fig. 6 Schematic of the experimental setup of droplet behaviors under supercritical conditions.

A novel and versatile droplet experimental setup was developed at Clark Atlanta University, which consists of a liquid pressurizing and transfer system, a high pressure/temperature chamber, a droplet formation, release and ignition system, and a high speed imaging system. The setup provides quiescent or convective environments under supercritical pressure and temperature conditions. Quiescent environment droplet gasification tests and convective environment droplet combustion tests were conducted under sub- and supercritical pressures with the setup. Specifically, the gasification rates of 1.5-mm-diameter suspended droplets were measured under different conditions (e.g. sub and super critical pressures). The characteristics of a free-drop non-combusting droplet (~1.5 mm diameter) and a free-drop

combusting droplet were studied using a high speed image system [27]. The images of droplet gasification and combustion revealed interesting phenomena and provided better understanding of the droplet behavior in sub and supercritical pressure environments. The preliminary results show that pressure has a significant effect on the characteristics of droplet gasification and combustion, such as the oscillatory deformation of a free-drop droplet, the buoyancy effects and flame propagation of a combusting free-drop droplet.

The experimental set-up is shown in Fig. 6 [27], which consists of a liquid-fuel supply system, a gas pressure-control system, a droplet formation system, a high-pressure chamber, an electrical igniter, and a high-speed CCD video system. Hexane was used for this preliminary study, which has a critical temperature of 507.7 °C, and a critical pressure of 436.6-psi (3.01 MPa) [28]. The experiments were carried out at pressures from 14.7 to 1200 psi, which covered sub and supercritical pressures of hexane.

The volumes/diameters of a suspended droplet were measured under different experimental conditions of 1000 frame/second and different pressures to measure its evaporation (gasification) rate. Figure 3 shows that the square of the diameter of the droplet vs. time is a straight line in most parts of the gasification period, because the gasification rate is proportional to the surface area of a droplet. However, Fig. 7 indicates that after their diameter square reduced to about 0.50 mm^2 (~0.8 mm in diameter) at 200 and 800 psi pressure, the gasification rate increased by a factor of about three because of surface tension increase. Figure 3 further shows that the gasification rate at 500-psi pressure was more than double those at 200 and 800 psi. This is thought to be the effect of supercritical conditions.

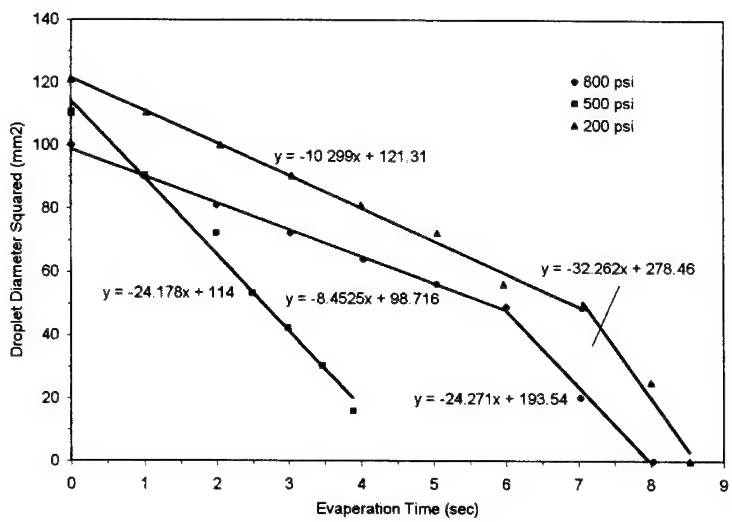

Fig. 7 The changes of the surface areas (diameter square) of droplets with gasification time under different pressures.

When a droplet was released from the thermocouple, it started to fall. The whole process was recorded by the high-speed video system at the recording speed of 1000 frame (picture) per second with an exposure time of 30 microseconds. By replaying the recorded image at a much slower speed (e.g. 1 – 30 frame/sec), the shape and speed of the falling droplet were measured.

It was found that during falling, the shape of a falling droplet was oscillating in the vertical direction. The magnitude of the oscillation changed with the system pressure, which reached its minimum at the droplet's supercritical pressure. From the recorded video images, it was observed that the system pressure has significant effects on the combustion of a free falling droplet. As the system pressure increases, the falling speed of a droplet proportionally decreased. When the chamber pressure was increased to a certain value (~200 psi), after falling below the igniter ring for a distance, the burning droplet floated up. As the chamber pressure further increased, the distance that the burning droplet would fall below the igniter ring decreased. As a combination effect, at a fixed time after its ignition, the distance of a free-burning-droplet falling-down decreased, as shown in Fig. 8. As the chamber pressure approached the droplet's supercritical pressure, the free burning droplet virtually stayed at its ignited position (Fig. 8).

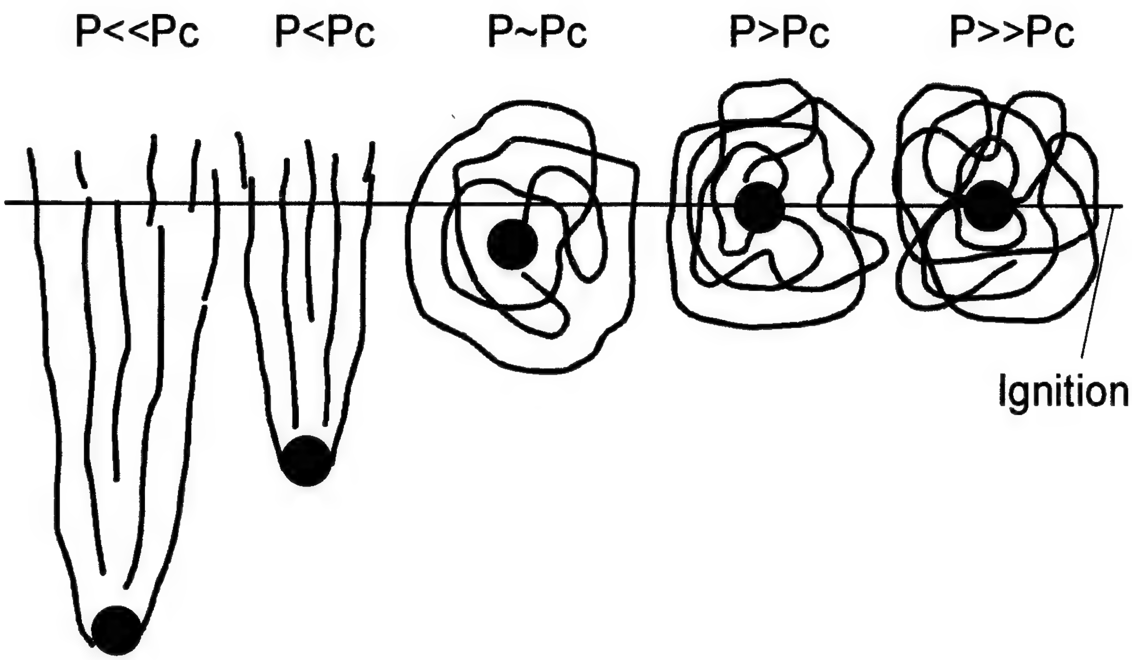

Fig. 8 The effect of the system pressure on the falling orbit of a free-falling burning droplet.

3.4 Combustion Instabilities in Ramjet Combustors

The objectives of this project are to study the mechanism that causes growth and sustenance of pressure oscillations, conduct detailed numerical analysis for characteristics of the turbulent flow field with oscillating combustion, and educate and train minority students in the field of aerospace engineering.

The experimental setup, shown in Fig. 9, consists of a ramjet combustor, an air supply and control system and a high-speed video imaging system. This system provides high pressures

for the flow through sonic nozzles that have been sized to give a stoichiometric mix of methane and air if the upstream pressures are equal. Two quartz windows are installed on sidewalls of the combustor for the velocity measurements by high-speed imaging system. Compressed air or mix was flowed through the combustor under ambient pressure and different flow rates. Fig. 10 shows that as the linear flow rate of air increased from 0.030 m/s (the picture at the left-top corner) to 3.7 m/s (the picture at the right-bottom corner) the flow changed from a laminar flow to a turbulent flow. At 0.037 m/s of the flow rate, a very clear V shape was formed along the top wall of the combustor (the picture at the left middle). When the flow rate increased to 0.37 m/s, a very strong vortex was formed.

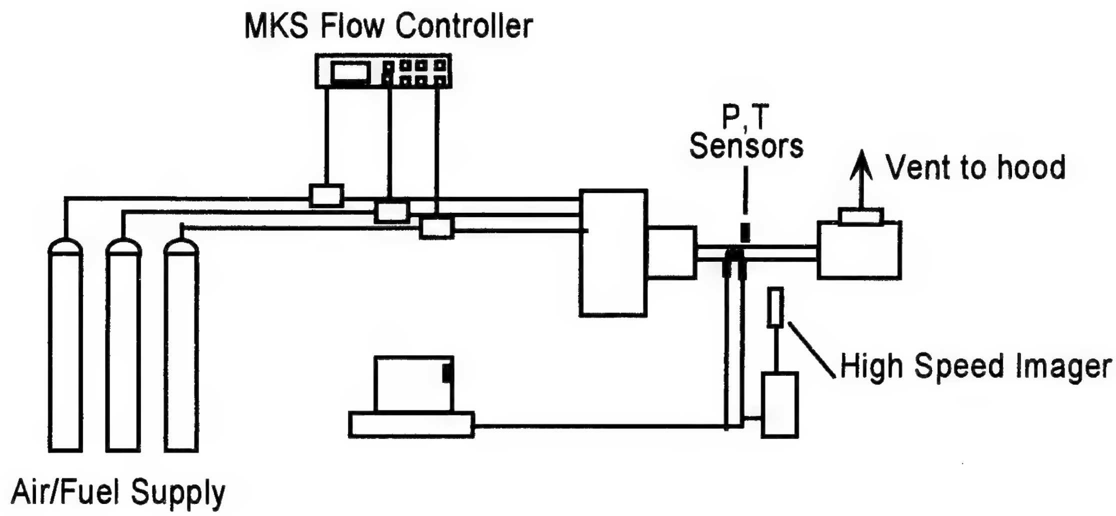

Fig. 9 Schematic of the experimental setup of combustion instabilities in ramjet combustors.

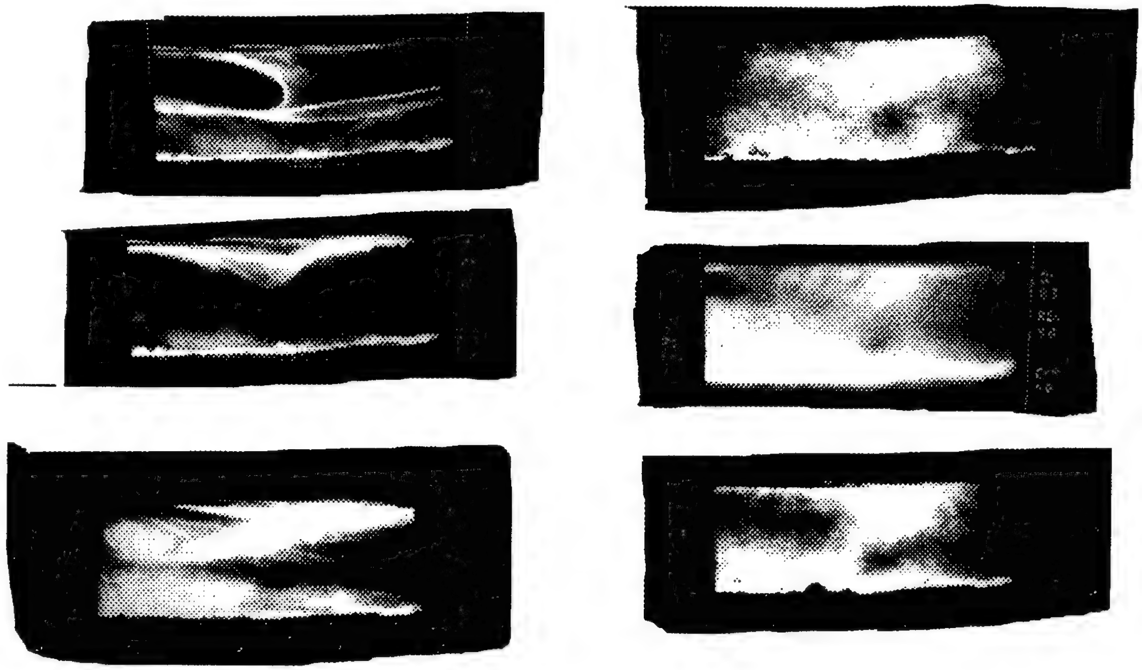

Fig. 10 Photos of ramjet flow by high speed imaging system under different flow rates.

4. CONCLUSIONS

- A laser Doppler velocimetry system and a high speed imaging system were purchased and installed in the Combustion and Emission Control Laboratory at Clark Atlanta University. These instruments have provided an integrated diagnostic system for flow visualization in the areas of combustion, propulsion, emission control, chemical kinetics and fluid dynamics.

- The instruments have significantly strengthened the University's research infrastructure, and enhanced CAU's capabilities to undertake research in the critical technology areas relevant to DoD. These include the chemical kinetics, combustion and propulsion, and fluid dynamics programs of the Army Research Lab (ARL); the aerodynamics, turbulence and internal flows, air-breathing combustion, space power and propulsion, and physical mathematics and applied analysis programs of the Air Force Office of Scientific Research (AFOSR); and the turbulence, propulsion and flow structure interactions, and propulsion programs of the Office of Naval Research (ONR).

- In the less than two years since the instruments have been purchased and installed, two DoD funded projects, *the nonthermal plasma discharge (NTPD) study, and the sub- and supercritical behavior of fuel droplets and jets,* and three NASA funded projects, *turbulent premixed combustion, droplet behavior under supercritical conditions and combustion instabilities in ramjet combustors*, have greatly benefited from the acquired instruments. Seven (7) technical papers and one (1) Ph.D. thesis have been produced using the acquired

facilities. So far, seven (7) undergraduate and graduate students from the Departments of Engineering and Chemistry at Clark Atlanta University have been trained and educated using the instruments by participating in the related research projects.

- In summary, all the objectives of the original proposal have been successfully achieved. The LDV and high speed imaging systems have become important, powerful and routine analytical and measuring instruments for research and education at Clark Atlanta University.

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APPENDIX A.

CLARK ATLANTA UNIVERSITY ATLANTA, GEORGIA

R 133063

PURCHASE ORDER ☒ CENTRAL SUPPLY REQUEST ☐

VENDOR TSI Incorporated phone: (612) 490.2811

ADDRESS 500 Cardigan Road, P. O. Box 64204, St. Paul, MN 55164

Ship to: Dr. Yaw D. Yeboah
Research Center, Rm 4061 880.6619

PURCHASE REQUISITION

SCHOOL OR DEPARTMENT Research Center for Science & Technoliogy DATE 5/1/97

BUDGET AFFECTED 266996-6510 Sub Ledger No. ____________ BUSINESS OFFICE BUDGET AFFECTED

QUANTITY		DESCRIPTION OF MATERIAL	UNIT PRICE	EXTENSION	
1	TRCF3	Three component optics with Colorburst, color link		$65,880	00
		fiberoptic capability			
1	9832	83mm Dia., Two Component fiberoptic probe for		18,950	00
		514.5 & 488mm, 350 mm F. D. Lens 10m Cable			
1	9831.13	83mm Dia. single component fiberoptic probe for	MAY 15 1997	16,020	00
		476.5 mm, 350 mm F. D. Lens 10m Cable			
2	IFA756	1 channel LDV Expansion for IFA 755	21,000	42,000	00
1	9422C	3 axis traverse for (2) 83 mm Dia. probes, 600		33,000	00
		x 600x600 mm travel			
1	6600	System integration service $2,500 for 1 day, $1500		4,000	00
		for second day			
		See Page 2 for Total			

ORDERED BY Yaw D. Yeboah APPROVED Arthur N. Clark PURCHASING AGENT APPROVAL

Dr. Yaw D. Yeboah

BUSINESS OFFICE 05/16/97

ORDER APPROVED BY
CAU-89 PURC. 1

CLARK ATLANTA UNIVERSITY ATLANTA, GEORGIA

PURCHASE ORDER XX CENTRAL SUPPLY REQUEST ☐ R 133042

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arch Center Rm. 4061 880.6619

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SCHOOL OR DEPARTMENT Research Center for Science and Technology DATE 5/1/97

BUDGET AFFECTED 266992-6510 Sub Ledger No. BUSINESS OFFICE BUDGET AFFECTED

QUANTITY	DESCRIPTION OF MATERIAL	UNIT PRICE	EXTENSION
2	Tuition Tuition for two persons at LDV Workshop at TSI in St. Paul., MN	$900	$ 1800.00
	Total System Price		$ 181650.00
	Discount for System Integraiton& Tuition		-5800 00
	Education Discount on Hardware		26377 00
	MAY 15 1997		
	Net Price after Discounts		$149473. 00

ORDERED BY Yaw D. Yeboah

Dr. Yaw D. Yeboah

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APPENDIX B.

284324

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ADDRESS 11633 Sorrento Valley Road, San Diego, CA 92121

Ship to: Dr. Yaw Yeboah
Research Center, Rm 2008 880-6619

PURCHASE REQUISITION

SCHOOL OR DEPARTMENT Research Center for Science & Technology DATE 5/11/97

BUDGET AFFECTED 266996-6510 Sub Ledger No. ________ BUSINESS OFFICE BUDGET AFFECTED

QUANTITY	DESCRIPTION OF MATERIAL	UNIT PRICE	EXTENSION	
1	1904945 Hi-Spec Promo Package		$35,000	00
1	1755230 Kodak Ektapro Hi-Spec Motion Analyzer 1012/2		0	00
1	8685968 1092 Frame Digital Frame Store		0	00
1	8821019 Kodak Ektapro High Gain Imager w/ 15' cable		0	00
1	1226711 6552-Frame Digital Frame Store		$28,500	00
1	1957018 Kodak Ektapro Intensified imager, model vsg		$37,525	00
1	1815745 Kodak Ektapro Intensified imager Controller		$10,260	00
1	8284085 Heavy duty tripod with precision gearhead.		$618	00
1	1768662 Video monitor, 13" high-resolution color	MAY 1 5 1997	$1,026	00
1	8754657 Arrilight lighting kit w/three lights		$2,296	00
1	8040776 28-105 mm Macro zoom lens, F/2.8, F-mount		$641	00
	See Page 2 for total..........			

ORDERED BY [signature] Dr. Yaw D. Yeboah

APPROVED [signature] PURCHASING AGENT APPROVAL
BUSINESS OFFICE

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05/16/97

CLARK ATLANTA UNIVERSITY ATLANTA, GEORGIA

PURCHASE ORDER [X] CENTRAL SUPPLY REQUEST [ ] R 133064

VENDOR Eastman Kodak Company

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SCHOOL OR DEPARTMENT Research Center for Science & Technology DATE 5/11/97

BUDGET AFFECTED 266996-6510 Sub Ledger No. ____ BUSINESS OFFICE BUDGET AFFECTED

QUANTITY	DESCRIPTION OF MATERIAL	UNIT PRICE	EXTENSION	
1	8468217 50mm Lens, F/.95, C-mount		$879	00
1	1933555 200mm Macro lens, F/4, F-mount		$1,330	00
1	8051781 F-mount to C-mount adapter		$198	00
1	8950966 Multi-channel data link 110V		$4,228	00
1	8384851 Computer access interface with transfer utility		$5,795	00
1	990555 Infinity model KV main		$5,600	00
1	990513 Infinity CFV-1/B Objectiv		$955	00
	Total Price		$134,851	00

MAY 15 1997

ORDERED BY Yaw D. Yeboah
Dr. Yaw D. Yeboah

APPROVED Arthur R. Clark PURCHASING AGENT APPROVAL
BUSINESS OFFICE 05/16/97

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	5b. GRANT NUMBER: N 00014-97-1-0511
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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A Laser Doppler Velocimetry system and a high speed imaging system were acquired and setup in the Combustion and Emission Control Laboratory at Clark Atlanta University. These instruments have provided an integrated diagnostic system in the areas of combustion, propulsion, emission control, chemical kinetics and fluid dynamics for time resolved flow visualization and detailed quantitative measurements of flow velocities in complex reacting and non-reacting flows. Two DoD funded projects, the nonthermal plasma discharge study and the sub- and supercritical behavior of fuel droplets and jets, and three NASA funded projects, turbulent premixed combustion, droplet behavior under supercritical conditions and combustion instabilities in ramjet combustors, have benefited from the instruments. In less than two years since the instruments were purchased and installed, seven (7) technical papers and one (1) Ph.D. thesis on their application have been produced.

15. SUBJECT TERMS

Laser Doppler Velocimeter, High Speed Video Imaging, Flow Visualization

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